



The Role of Artificial Intelligence in Enhancing Food Supply Chain Efficiency and Reducing Waste: An Analytical Perspective on Global Indicators and Future Trends

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Abstract:

This research addresses the structural imbalance in the global food system, where approximately one-third of annual production (totaling 1.05 billion tonnes in 2022) is wasted despite 780 million people facing chronic hunger. The study critiques traditional supply chain models for being reactive and fragmented, highlighting Artificial Intelligence (AI) as a transformative tool for proactive management through predictive analytics and IoT. Empirical indicators demonstrate that AI integration enhances demand forecasting accuracy up to 95%, reduces retail waste by 20%–50%, and increases profitability by 25%. The study concludes that the global impact of AI remains limited by digital infrastructure gaps in developing nations and insufficient pre-production data. Finally, it recommends incorporating AI systems into national food security policies to finance data measurement and ensure systemic resource sustainability.

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1. Introduction

Food waste represents one of the most complex economic imbalances within the global food system. International estimates suggest that approximately one-third of all food produced annually is lost or wasted across various stages of the supply chain. This occurs at a critical juncture where the world is witnessing a marked increase in food insecurity and a widening gap between food supply and demand. The repercussions of this phenomenon extend beyond direct economic losses; they encompass profound environmental and social impacts, including the inefficient depletion of natural resources, rising carbon emissions, and the heightened vulnerability of populations most at risk of food instability.

In this context, the complexity of food supply chains has escalated due to globalization, accelerating consumption patterns, and a proliferation of stakeholders. Furthermore, the increasing frequency of shocks—linked to climate change, health crises, and geopolitical tensions—has exposed the limitations of traditional models in managing food flows with high efficiency. Consequently, there has been a surge of interest in **Artificial Intelligence (AI)** applications as a pivotal tool for digital transformation, given their capacity to enhance demand forecasting accuracy, rationalize inventory management, and optimize transport and storage efficiency.

However, a critical review of the existing literature reveals that most studies addressing AI in food supply chains have focused primarily on optimizing operational performance or reducing costs within specific stages or sectors. These studies often lack an integrated vision that links these applications to food waste levels across the entire value chain. Conversely, reports from international organizations—notably the Food and Agriculture Organization (FAO) and the United Nations Environment Programme (UNEP)—have concentrated on quantifying food loss and waste and analyzing its geographical and sectoral distribution. Yet, these reports have not

sufficiently integrated dynamic analytical models capable of preempting waste and redirecting food surpluses before they occur.

Accordingly, this study addresses a central problematic: To what extent can Artificial Intelligence, when deployed within an integrated framework, enhance food supply chain efficiency and curtail food waste on a comprehensive scale, rather than merely at the level of micro-operational or local processes. More specifically, the article poses the following question: ***How can AI transition from a tool for operational efficiency into a proactive mechanism for redirecting food surplus and mitigating waste at its source?***

2. Conceptual and Theoretical Framework

2.1 The Concept of Food Supply Chains (FSC)

The food supply chain is fundamentally defined as "a network of facilities, individuals, activities, technology, and information aimed at transforming raw materials into final products delivered to the consumer" (Ali, 2019). Building on this, Keogh describes it as "a network of stakeholders working collaboratively to ensure the delivery of safe food products, wherein all parties are committed to executing a series of activities that facilitate the transformation of food from raw material to a finished product." (Keogh, 2020)

More specifically, the Agri-food Supply Chain (AFSC) is defined as "a complex system responsible for the movement of agri-food products from the production stage to the consumption stage. Throughout these stages, supply chain actors strive to meet consumer demand for agri-food products while maintaining their quality and safety". (Zhao, 2019)

2.2 The Concept of Artificial Intelligence (AI)

Definitions of Artificial Intelligence vary, yet they converge on its role in replicating cognitive functions. Key perspectives include:

Cognitive Simulation: AI refers to the simulation of human intelligence processes by machines, especially computer systems. These processes include learning (the acquisition of information and rules for using it), reasoning (using rules to reach approximate or definite conclusions), and self-correction. Notable applications include expert systems, Natural Language Processing (NLP), speech recognition, machine vision, and generative tools such as ChatGPT and Perplexity. AI infrastructure requires specialized hardware and software for developing and training machine learning algorithms, commonly utilizing programming languages such as Python, R, Java, and C++. (Lev, 2024) AI is a technology that enables computers and machines to simulate human learning, comprehension, problem-solving, decision-making, creativity, and autonomy. AI-equipped applications and devices can identify objects, understand and respond to human language, learn from new information and experiences, and provide detailed recommendations to users and experts. Furthermore, they can act autonomously, reducing the necessity for direct human intervention—a classic example being autonomous vehicles. (Cole, 2025)

Complementing these definitions, researcher Daniel Fagella synthesized various perspectives from credible sources and expert feedback to propose a functional definition: "Artificial Intelligence is an entity capable of receiving inputs from the environment, interpreting and learning from them, and exhibiting related behaviors and flexible actions that assist the entity in achieving a specific goal within a defined period" (Vladan Devedzic, 2022). In this conceptualization, Fagella distinguishes between AI as a functional entity and AI as a broader field of research and study.

In the wake of rapid advancements in e-agriculture technology, AI has emerged as a transformative force in three primary domains: Agricultural Robotics, Soil and Crop Monitoring, and Predictive Analytics. (Nazish Aijaz a, 2025)

AI technology empowers farmers to make more informed, data-driven decisions, leading to higher efficiency in both crop and livestock production. It plays a pivotal role in modern agriculture by leveraging data and Machine Learning (ML) to (Gupta, 2025):

1. Optimize farming practices and predict yield outcomes.
2. Enhance resource management through real-time soil and crop analysis.
3. Utilize predictive analytics to detect crop diseases, weeds, and pests early.

Furthermore, Expert Systems (ES) represent a critical branch of AI within this context. These systems provide software capabilities that enable computers to perform tasks that traditionally required human expertise. They achieve this by utilizing knowledge bases and advanced techniques such as Rule-Based Systems, Fuzzy Logic, and Hybrid Systems (Navid Zarbakhshnia, 2019) .

Modern AI techniques, such as Simulation and Agent-Based Modeling (ABM), further contribute to a deeper understanding of systemic dynamics. These tools are instrumental in optimizing decision-making processes within supply chain management by simulating complex interactions between various stakeholders and environmental variables . (Efpraxia, 2022)

3. Methods and Materials:

The study adopts a multi-dimensional research methodology that integrates a critical literature review with a rigorous quantitative approach. To bridge the gap between AI deployment and food security, a conceptual framework was formulated for proactive decision-making. The empirical validity of the study is supported by cross-regional comparative analysis and statistical tabulation of global data aggregated from authoritative sources, including the FAO, UNEP, and the World Bank. By synthesizing performance metrics like the Logistics Performance Index (LPI) with AI readiness indices,

the research systematically evaluates the operational impact of digital accounting on reducing food waste across the global supply chain."

4. Results and discussion

4.1.Indicators and Analysis: Recent Trends

a) Indicator 1: Global Food Waste and Proportionate Ratios

Recent data underscores the magnitude of the global food waste crisis. Analyzing the period between 2019 and 2022 reveals critical points of loss across the supply chain, from post-harvest stages to the final consumer level.

✓ Global Food Waste Trends (2019–2022)

Table 01: Global Food Waste Evolution and Percentage of Total Output (2019–2022)

Year	Total Global Food Waste (Tonnes)	Percentage of Total Food Production	Data Source / Observation
2019	931 Million	17%	UNEP Food Waste Index Report (UNEP, The Food Waste Index Report 2021, 2021) (UNEP organization, 2021)
2020	Data Unavailable	Data Unavailable	Lack of comprehensive data due to the impact of the COVID-19 pandemic on global production and consumption patterns.
2021	Inconclusive	Inconclusive	No official global reports published; however, preliminary data suggested levels similar to 2019, with slight localized decreases due to increased awareness and mitigation policies.
2022	1.05 Billion	~19%	UNEP Food Waste Index Report (UNEP, 2024)

Source: Compiled by the researcher based on the aforementioned institutional sources.

Note: Official publications, such as the *Food Waste Index Report 2024*, provide retrospective data (in this case, for the year 2022). As of the current date, no independent, verified reports have been released by the UNEP or FAO providing comprehensive global food waste data for the period following 2022.

✓ Data Analysis and Discussion

- **Substantial Increase in Waste Volume:** There is a marked escalation in the volume of food waste, rising from approximately **931 million tonnes** in 2019 to nearly **1.05 billion tonnes** in 2022. This represents an absolute increase of roughly **119 million tonnes** within a three-year span.
- **Expansion of the Waste-to-Production Ratio:** The proportion of food wasted relative to total production available for consumption rose from **17% to approximately 19%**. To place this in a more representative context: a 17% waste rate implies that for every five cups of food produced, one cup is wasted. This signifies a massive loss from both an economic efficiency and environmental sustainability perspective.
- **Upward Trend Resilience:** The data confirms that global food waste is not receding; rather, it exhibited a steady upward trajectory through 2022. This trend persisted despite significant shifts in global supply chains, including the structural shocks caused by the **COVID-19 pandemic**.
- **Systemic Deep-Rootedness:** These figures indicate that food waste is deeply embedded across multiple stages of the supply chain, rather than being confined solely to the consumer level. This systemic nature will be further evidenced by the subsequent indicator ; regarding the diversification of loss sources and their global distribution.
- **Data Fragility and the Case for AI:** The lack of detailed official data for 2020 and 2021—a direct consequence of the pandemic—exposes the fragility of current global data collection systems. It

suggests that global supply chain management challenges have not yet mitigated the intensity of waste.

✓ **Conclusion of Analysis**

These trends underscore the critical necessity of adopting advanced data analytics and **Artificial Intelligence (AI)** to proactively reduce waste across the entire value chain. The findings strongly support the transition toward innovative solutions such as:

- **Intelligent Demand Forecasting:** To align production more closely with actual consumption.
- **Smart Inventory Management:** To optimize the shelf-life and turnover of perishable goods.
- **Real-Time Data Analytics:** To identify and rectify bottlenecks before they result in physical waste.

b) **Indicator 2: Diversification of Food Loss and Waste Sources and Global Distribution**

The following table provides a multidimensional breakdown of food loss and waste (FLW) for the year 2022. It distinguishes between "Loss" (occurring post-harvest up to the retail stage) and "Waste" (occurring at the retail and consumption levels), while also highlighting the environmental and socio-economic paradoxes inherent in the current system.

Table 02: Sources, Volumes, and Global Distribution of Food Loss and Waste (2022)

Dimension	Metric / Value (2022) ~
Post-Harvest Loss Rate (Pre-retail)	13.2% of total food produced
Waste Rate (Retail and Consumer level)	19% of food available to consumers
Total Food Waste (Absolute Volume)	1.05 Billion Tonnes
Household Food Waste	631 Million Tonnes (≈60% of total waste)

Food Services Waste	290 Million Tonnes ($\approx 28\%$ of total waste)
Retail Sector Waste	131 Million Tonnes ($\approx 12\%$ of total waste)
Annual Per Capita Waste	79 kg per person
Environmental Impact (GHG Emissions)	8–10% of total global greenhouse gas emissions
Socio-Economic Paradox (Hunger)	Despite this waste, ~ 780 million people face chronic hunger
Highest Commodity Loss (Fruits & Veg)	25.4% of total production
Highest Regional Loss (Sub-Saharan Africa)	23.0%
Lowest Regional Loss (N. America / Europe)	10.0%

Source: Compiled by the researcher based on UN Environment Programme (UNEP) and Food and Agriculture Organization (FAO) reports. (UNEP, 2024), (FSSC, 2024) (FAO, 2024))

1. Analytical Insights:

- **The Household Dominance:** Contrary to common perceptions that waste is primarily a logistics or industrial issue, the data shows that **60% of waste occurs at the household level**. This suggests that AI applications must extend beyond supply chain logistics into consumer-facing "Smart Home" and "Smart Retail" technologies to influence behavioral change.
- **The Perishability Crisis:** Fruits and vegetables suffer the highest loss rate (**25.4%**). This highlights a critical failure in cold chain management and real-time inventory tracking, areas where **AI-driven IoT (Internet of Things)** sensors can provide significant intervention.
- **Regional Disparities:** The high loss rate in Sub-Saharan Africa (**23%**) vs. North America (**10%**) points to "Loss"

(infrastructure/storage issues) being the primary challenge in developing economies, whereas "Waste" (consumer behavior) is the focus in developed regions.

- **Environmental Externalities:** With food waste contributing up to **10% of global emissions**, reducing waste is no longer just an economic necessity but a primary lever for climate change mitigation.

2. Critical Synthesis of Findings

- **The Global Moral and Economic Paradox:** The starkest finding is the systemic contradiction between waste and want: while over **one billion tonnes** of food are discarded, approximately **780 million people** continue to suffer from chronic hunger and malnutrition worldwide. This disparity necessitates a paradigm shift toward more efficacious solutions. Reducing food waste is not merely a technical optimization; it is a vital strategy to bridge the "food gap" and mitigate the global crises of food insecurity and undernutrition that threaten global stability.
- **Distributed Systemic Failure:** The data illustrates that the challenge of food waste is not confined to a single bottleneck. Instead, it is a distributed failure across the entire value chain:
 - ✓ **Upstream (Production & Storage):** Infrastructure deficits and inefficient harvesting.
 - ✓ **Midstream (Transport & Logistics):** Failures in the cold chain and predictive distribution.
 - ✓ **Downstream (Retail & Consumption):** Behavioral patterns and market overstocking.

3. The Path Forward

Addressing this multi-stage challenge requires more than traditional logistics; it demands an integrated, AI-driven approach capable of synchronizing these disparate stages.

c) Artificial Intelligence in Food Supply Chains: Data and Experiences

The integrative links between studies in food science and technology, the food sector, and Artificial Intelligence (AI) have proven to be one of the most compelling fields for academics, scientists, and industry specialists in recent decades. In the current food manufacturing cycle, AI is involved in every step of the process, from sorting to analysis and packaging. Additionally, it is highly beneficial to consider consumer satisfaction, alongside issues related to the food supply chain and distribution during the consumption stage (Vilhoughrenuo Zatsu, 2024) .

d) The Role of AI across Different Supply Chain Stages

The role of AI varies according to the different stages of the supply chain, as illustrated in the following table:

Table 03: Relationship between Artificial Intelligence and Supply Chains

Supply Chain Stage	Role of Artificial Intelligence	Impact
Production	Analyzing weather and soil data to predict crop yield and quality (integrating historical data with satellite imagery and ground sensors).	Reduction of agricultural losses.
Storage	Tracking product status via the Internet of Things (IoT) (Smart alarm systems to report conditions that may lead to product spoilage).	Reduction of spoilage during storage.
Transportation	Optimizing shipping routes and smart refrigeration management.	Lowering costs and emissions.
Distribution	Forecasting demand within local markets.	Reduction of surplus and waste.
Retail	Smart inventory management based on actual demand.	Reducing waste and increasing profits.

Source: Compiled by the researcher based on: FAO (2023), McKinsey (2024), PwC (2 024), WEF (2023), UNEP (2024)

Data Analysis:

- The table demonstrates how AI transforms the supply chain from a traditional reactive process into a proactive, intelligent, and sustainable chain that reduces waste on a global scale. AI covers all stages of the food supply chain from production to retail, representing a comprehensive strategy that links data, analysis, forecasting, and real-time decision-making.

e) The Empirical Impact of AI Adoption in Supply Chains

The following table delineates the global economic and environmental costs of food waste alongside the measurable performance gains observed in entities that have integrated Artificial Intelligence into their supply chain operations by the end of 2024.

Table 04: Global Food Waste Impacts vs. AI Adoption Outcomes (End of 2024)

INDICATOR	VALUE / PERCENTAGE	SOURCE
GLOBAL FOOD WASTE VOLUME	1.09 BILLION TONNES / YEAR	FAO (2024)
ECONOMIC LOSSES FROM WASTE	\$940 BILLION / YEAR	UNEP (2024)
CARBON EMISSION CONTRIBUTION	8% OF GLOBAL EMISSIONS	IPCC (2024)
DEMAND FORECASTING ACCURACY	80% – 95% (IN AI-INTEGRATED FIRMS)	MCKINSEY (2024)
WASTE REDUCTION IN RETAIL	20% – 50% (FOLLOWING AI ADOPTION)	WEF (2023)
PROFITABILITY INCREASE	+15% TO +25% (IN AI-AUTOMATED CHAINS)	PWC (2024)

Source: Compiled by the researcher based on the cited institutional data.

Data Analysis:

The indicators presented in Table 04 provide empirical evidence that AI adoption serves as a critical catalyst for structural efficiency. Key insights include:

- **Waste Mitigation:** The integration of AI technologies contributes to an average global reduction in food loss and waste of **38%**.
- **Operational Optimization:** Beyond waste reduction, AI enhances overall supply chain efficiency by an average of **25%**.
- **The Business Case for Sustainability:** The data reveals a strong positive correlation between automated intelligence and profitability (up to **25% increase**), suggesting that the transition to AI-driven chains is not only an environmental necessity but a primary driver of competitive advantage and financial viability in the global food market

e) Practical Case Studies in Artificial Intelligence Adoption

AI tools have recently demonstrated a profound practical impact on waste reduction through various international initiatives. The following cases highlight successful interventions:

1. United Kingdom: Industrial Waste Mitigation

In a high-profile pilot supported by **Innovate UK** and industry giants such as **Nestlé**, an AI-driven tool was deployed to identify and restrict edible waste within production lines. The results were significant: a **87% reduction in edible waste** within just two weeks. The study revealed the potential to save up to **700 tonnes of food** (approximately 1.5 million meals), while mitigating **1,400 tonnes of CO2 emissions** and saving millions of pounds in operational costs (theguardian., 2025).

2. Winnow AI: Hospitality and Food Services

The **Winnow AI** system is utilized in hotels and restaurants to identify food waste through image recognition and weight analysis. This intervention has led to a reduction in food waste by up to **76%** in several hospitality facilities' (Dean, 2024)

3. Retail Sector: Perishable Goods Optimization (Muhammad Hassan Ghulam Muhammad and all, 2025)

Advanced analytical systems utilizing **Machine Learning** and **Time-Series Forecasting** have been implemented to optimize orders for highly perishable products (e.g., meat, vegetables, dairy). These systems achieved:

- A **20% to 30% reduction** in waste.
- **Real-time inventory management**, aligning supply with immediate demand.
- Optimized stock allocation based on seasonal demand and consumer behavior.

The models utilized historical sales data, consumption patterns, and even weather forecasts to adjust procurement orders dynamically (*Southern Journal of Nanosciences*).

4. Global Corporate Applications:

- **Amazon:** Leverages intelligent forecasting and warehouse automation to minimize order processing times (amazon, 2026).
- **DHL:** Implements smart route planning to reduce transportation costs and enhance delivery precision (Yuxia Mou, 2024).

Data-Driven Distribution and Inventory Planning

- An academic paper published on **arXiv** examines how **JD.com**, one of China's largest e-commerce and logistics companies, uses **data-driven approaches for integrated assortment planning and inventory allocation** to improve supply chain performance. The study highlights the development of algorithms that integrate **forecasting, optimization, and simulation** to minimize lost sales and inventory transfer costs, improve stock availability, and increase local order fulfillment rates—thereby enhancing distribution planning and inventory management across its network of regional and front distribution centers.

- **Conclusion of Case Analysis**

These case studies demonstrate that Artificial Intelligence provides more than mere theoretical solutions; it delivers measurable results in reducing waste within real-world food industries.

f) **Why is the Global Impact of Artificial Intelligence Still Limited?**

Despite the impressive results of specific applications, Artificial Intelligence is still in the nascent stages of its true transformative role. This is evidenced by the clear gap between technological potential and the global outcomes achieved thus far, as shown in the previous data. This limitation is primarily due to several key factors:

- **Scarcity of Accurate Pre-Manufacturing and Harvest Data:** In developing nations, data from farms is often neither collected nor analyzed sufficiently, which diminishes the efficacy of advanced predictive models.
- **Disparities in Digital Infrastructure:** Countries with robust digital infrastructure are improving at a significantly faster rate than others, widening the technological divide.
- **Lack of Integration Across Supply Chain Stages:** AI systems are often deployed in isolation (focusing solely on demand forecasting or storage optimization). True solutions require comprehensive integration across the entire value chain.
- **Fragmented or Non-Comprehensive Applications:** Current applications are often restricted to specific stages of the supply chain or limited geographical regions. This fragmentation complicates the coordination required to redirect food loss toward areas facing acute hunger.

Final Conclusion:

- ✓ Global food waste has reached structurally alarming levels, exceeding 1 billion tonnes annually, representing nearly 19%

of total food production, while hundreds of millions still face chronic hunger.

- ✓ Food loss and waste are systemic and distributed across all stages of the supply chain (production, storage, transport, retail, and households), indicating structural inefficiencies rather than isolated operational failures.
- ✓ Empirical evidence confirms that Artificial Intelligence significantly enhances supply chain performance:
 - ✓ Demand forecasting accuracy reaches up to 95%.
 - ✓ Retail waste reduction ranges between 20% and 50%.
 - ✓ Profitability increases by up to 25%.
 - ✓ Industrial case studies report waste reductions exceeding 70%.
- ✓ AI shifts food supply chains from a reactive management model to a predictive and preventive system capable of anticipating surplus, optimizing allocation, and reducing waste at its source.
- ✓ However, the global impact of AI remains limited due to:
 - ✓ Weak digital infrastructure in developing regions.
 - ✓ Insufficient pre-production and farm-level data.
 - ✓ Fragmented and non-integrated AI applications.
 - ✓ Lack of incorporation into national food security policies.
- ✓ Therefore, AI can move beyond operational optimization to become a proactive mechanism for surplus redirection and systemic waste reduction—provided that it is implemented within an integrated, data-driven, and policy-supported framework.
- ✓ The study concludes that Artificial Intelligence is not merely a technological enhancement tool, but a strategic lever for restructuring the global food system toward greater efficiency, sustainability, and food security.

a) Recommendations:

- Incorporate AI systems for food chains into local and national policy frameworks.
- Finance data measurement projects for both pre- and post-production stages.

- Establish cross-sectoral collaborations to deploy integrated AI systems globally.

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